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Graphene-Based Terahertz Waveguide Amplifier

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Abstract

Graphene has been considered as an ideal material for electronic applications because of its high carrier mobility and thermal properties. Here, we study the conductivity of graphene at terahertz (THz) frequency range. Light can tune the conductivity of graphene and it has been shown that optically pumped multiple graphene layer (MGL) presents negative conductivity in THz region due to inter-band population inversion. With use of this property THz travelling-wave amplifier based on optically pumped MGL has been introduced in this article. The gain characteristics of the amplifier at room-temperature have been obtained as a function of graphene layers and the Fermi level of layers. The obtained results are promising for next generation THz communications.

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1. Introduction

THz wave generation and amplification with sufficient output power at room temperature have attracted great attention in the recent years. The maximum operating power of semiconductor-based THz amplifiers is limited by electron velocity. At the other hand, THz amplifiers are affected by thermal noise at room temperature since the band gap energy contributing to lasing oscillation is small, Takatsuka et al. (2012).

Beside these advancements in THz technology, outstanding developments have been occurred in the field of plasmonics, such as integrated photonic circuits, Gramotnev et al. (2011), Tao et al. (2012) and bio sensing (Anker et al. (2008). Recently, graphene plasmonics have attracted considerable attention, which has shown interesting

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properties including extremely large mode confinement verified by experiments Chen et al. (2012), Fei et al. (2012), chemically or electrostatically tuned optical response of grapheme, Schwierz (2010) and longer propagation distance of graphene surface plasmon waves compared to metallic surface plasmon waves Jablan et al. (2009), Christensen et al. (2011).

Graphene-based devices have shown high potential for operation at THz frequencies due to the frequency of graphene plasmons and the band gap of graphene nano ribbons. It has been shown that optical pumping an epitaxial multiple graphene layer structure with photon energy of $\hbar\Omega$ leads to the generation of electrons and holes with energy $\hbar\Omega/2$. The photo generated electrons and holes quickly emit cascades of N optical phonon where N means the integer part of x and $\hbar\omega_0 = 200$ meV is optical phonon energy in grapheme, Ryzhii et al. (2009).

The photo-generated electrons (holes) occupy the states with the energy $\mathcal{E}_N = \hbar\Omega/2 - N\hbar\omega_0$ since the recombination time τ_R (1-100ns) is much larger than the energy relaxation time τ (1-3ps) of optical phonon scattering and the electron-hole carriers have not enough time to recombine. Thus, inter band transitions with energies $\hbar\omega < 2\mathcal{E}_f$ result in negative contribution to the real part of the optical conductivity. For $\text{Re}\sigma_\omega < 0$, the stimulated emission of photons with relatively low energy $\hbar\omega$ (at THz rang) is possible. Graphene-based lasers have been introduced theoretically in the literature recently, Ryzhii et al. (2010).

Based on the same formalism, we report on a travelling wave-THz waveguide amplifier composed of graphene layers deposited on SiC substrate in this article. The gain characteristics for the proposed structure have been obtained as a function of graphene layers properties such as layer numbers and Fermi level of the layers.

2. Theoretical Background

A MGL structure deposited on SiC substrate has been considered for the amplifier structure as illustrated in Fig. 1. It has supposed that the MGL structure comprises K upper GLS and a highly conducting bottom layer with a Fermi energy of $\mathcal{E}_B = 400$ meV. The electron and hole distributions in the range of energies $\mathcal{E} < \hbar\omega_0$ in the k -th graphene layer can be described by the Fermi functions with the quasi-Fermi energies $\mathcal{E}_f^{(k)}$. Using the Falkovsky-Varlamov formula for the dynamic conductivity of on MGL structure generalized for non-equilibrium electron-hole systems (Falkovsky 2008), one can write the conductivity of graphene layers as

$$\begin{aligned} \text{Re}\sigma_\omega^B = & (e^2 / 4\hbar) \{ [1 + \exp(\frac{\hbar\omega/2 - \mathcal{E}_f^B}{k_B T})]^{-1} - [1 + \exp(\frac{\hbar\omega/2 + \mathcal{E}_f^B}{k_B T})]^{-1} \} \\ & + (e^2 / 4\hbar) \frac{4k_B T \tau_B}{\pi\hbar(1 + \omega^2 \tau_B^2)} \text{Ln}[1 + \exp(\mathcal{E}_f^B / k_B T)] \end{aligned} \quad (1)$$

$$\text{Re}\sigma_\omega^{(k)} = (1/2)(e^2 / 4\hbar) \tanh(\frac{\hbar\omega - 2\mathcal{E}_f^{(k)}}{4k_B T}) + (e^2 / 4\hbar) \frac{8k_B T \tau}{\pi\hbar(1 + \omega^2 \tau^2)} \text{Ln}[1 + \exp(\mathcal{E}_f^{(k)} / k_B T)] \quad (2)$$

τ_B and τ are the electron and hole momentum relaxation time in the bottom and other GLS. The first and second terms in the right hand sides of equations (1) and (2) correspond to the interband and intraband transitions, respectively. Since Fermi energy of the bottom graphene layer is $\mathcal{E}_B = 400$ meV, one can ignore the interband part of conductivity in bottom graphene layer.

Optical gain under field propagation in the structure can be calculated using the waveguide-dependent gain relation described by Ryzhii et al. (2010)

$$g_\omega = \frac{4\pi \text{Re}\sigma_\omega}{c\sqrt{\epsilon_s}} \Gamma_\omega - \alpha_\omega \quad (3)$$

Where the confinement factor of the designed waveguide is described by

$$\Gamma_{\omega} = \left(\int_{-D/2}^{D/2} |E_{\omega}(y, 0)|^2 dy \right) / \left(\int_{-D/2}^{D/2} \int_{-\infty}^{\infty} |E_{\omega}(y, z)|^2 dy dz \right) \quad (4)$$

$\alpha_{\omega} = 2 \text{Im}(\beta)$ is the absorption coefficient of the propagating mode and β is the wave number of the propagating mode. The mode characteristics along with the effective refractive index of the waveguide are obtained using a mode-solver software. Assuming $\varepsilon_F^B = 400 \text{ meV}$, $\hbar\Omega = 920 \text{ meV}$, $\tau = 10 \text{ ps}$ in our calculation the $\text{Re} \sigma_{\omega}$ and gain are calculated as a function of frequency for different numbers of GLs with $\varepsilon_r = 50 \text{ meV}$ in Fig. 2.

As it can be seen from Fig.2, increasing the number of graphene layers results in increasing the real conductivity ($\text{Re} \sigma_{\omega}$) toward negative values. In the other words, increasing the number of graphene layers leads to larger absorption of the optical pumping which in turn leads to higher gain values.

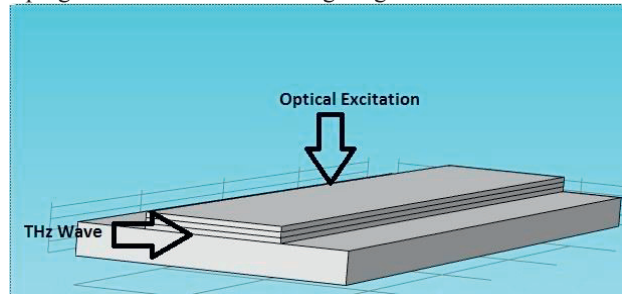


Fig. 1. Schematic view of the proposed amplifier based on MGL structure.

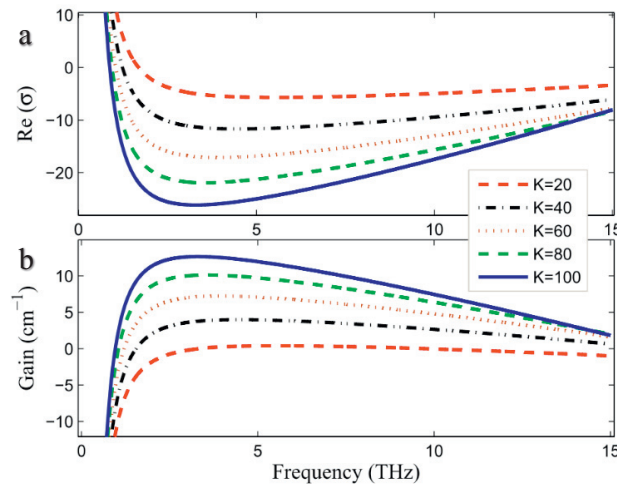


Fig. 2. (a) Real part of conductivity; (b) optical gain. Of MGLs as a function of number of layers ($K=20, 40, 60, 80$, and 100).

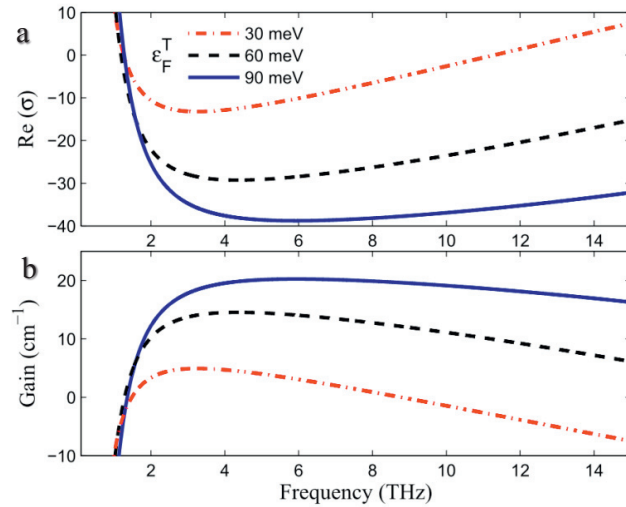


Fig. 3. (a) Real part of conductivity; (b) optical gain. Of MGLs as a function of optical pumping intensities represented by $\varepsilon_F^T = 30, 60, 90$ meV.

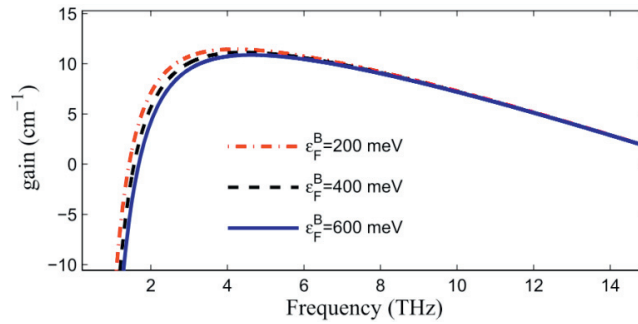


Fig. 4. Optical gain versus frequency as a function of Fermi level of bottom graphene layer ($\varepsilon_F^T = 50$ meV).

It should be mentioned that the values for real part of conductivity are normalized by $e^2 / 4\hbar$. Also, the sign of $\text{Re}\sigma_\omega$ is positive for frequencies higher than 15 THz. Although a minimum is observed at frequencies around 3 THz.

Figure 3 shows the frequency-dependency of $\text{Re}\sigma_\omega$ and gain calculated for MGL structure with different values of ε_F^T (i.e. different optical pumping intensities). Because of weak absorption of Optical radiation in each GL (2.3 percentage of optical radiation), it is essential to increase optical pumping intensity for gain improvement.

The highly conducting bottom GL, which grows due to the intrinsic features of the MGL structure growth mechanism, also, affects the optical gain of the amplifier since it results in absorption of the THz radiation emitted by other GLs, Ryzhii et al. (2009).

Regarding the absorption increase with decreasing frequency, obtaining negative conductivity in the MGL structures with a conducting bottom layer becomes difficult. In contrast, decreasing the Fermi energy and consequently the electron density in the bottom GL, promotes the achievement of negative conductivity in a wide frequency range. Fig. 4 illustrates the optical gain as a function of Fermi energy of the bottom GL ($\varepsilon_F^B = 200, 400, 600$ meV) where $\varepsilon_F^T = 50$ meV has been assumed. Although the effect of increasing the Fermi level of bottom GL is not considerable at higher frequencies, this effect is clear at lower frequency range.

3. Conclusion

A travelling wave graphene-based waveguide amplifier was proposed in this article which operates based on the recently developed idea of far-infrared and THz lasing potential in MGL structures. The waveguide structure (consisted of a SiC substrate and deposited MGLs) was designed so that the fundamental optical mode could propagate in the structure. Simultaneous optical pumping the graphene layers provides the possibility of population inversion at room temperature and hence, optical gain is obtained. The effect of layer numbers and also, Fermi level of layers were also investigated.

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